On MIMO Signal Processing for Adaptive W-CDMA and OFDM Wireless Transceivers

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Abstract—**In this paper, we consider wideband extensions of narrowband signal processing techniques for MIMO wireless transceivers. The extensions are applied and analyzed on commonly used wideband systems such as W-CDMA and OFDM. We focus on signal processing techniques for channel estimation and correction, including pilot-aided and decision-directed LMS-based adaptive estimation. Simulation study compares cases with one and two transmit/receive antennas and shows that BER of W-CDMA system consistently improves by exploiting multi-path diversity through additional antenna at the receiver, while additional transmit antenna is beneficial under specific channel conditions. BER performance in OFDM is more sensitive to the value of the channel's smallest eigen-value than to the eigen-spread. In most practical cases, therefore, the sub-channels with small eigen-values are not usable due to poor BER.**

1 Introduction

High data rate communication systems employ sophisticated signal processing techniques in order to achieve spectrally efficient communication links in the limited radio spectrum. Most efficient solutions at the physical layer are demonstrated in cellular systems using spread spectrum code division multiplex access (CDMA), and indoor wireless local area networks (WLAN) using orthogonal frequency division multiplexing (OFDM). Both techniques use temporal signal processing to mitigate the intersymbol interference (ISI) introduced by wideband frequency selective fading channel. Recent research on multiple-input multiple-output (MIMO) systems [1] claims that spectral efficiency can be improved by combining temporal processing with spatial processing that exploits spatial dimension of the wireless channel. Such space-time processing operates with multiple transmit/receive (Tx/Rx) antennas and improves the link capacity by exploiting diversity and multiplexing gain [2]. It also reduces the co-channel interference (CCI) and further mitigates the ISI by spatial filtering. Foschini has shown that capacity grows linearly with the number of antennas in narrow-band flat-fading channels [3]. This gain is attributed to *spatial multiplexing*. However, in wideband systems, the capacity gain due to combined time and spatial processing depends not only on the frequency selectivity of wideband MIMO channel, but also on the relationship, sequence, and implementation of signal processing algorithms used for space-time processing.

In this paper we study two different space-time structures for wideband MIMO systems with different sequencing of temporal and spatial processing, and analyze their preformance in typical wideband channels. First system employs CDMA Rake receiver to combat multi-path channel, and uses adaptive antenna array at the receiver and/or space-time coder at the transmitter to utilize the channel diversity. The second system is based on OFDM with the adaptive space-time algorithm based on narrowband singular value decomposition (SVD) which is applied on each sub-carrier in OFDM stream.

2 Models of CDMA and OFDM MIMO Systems

For CDMA study we adopted the downlink channel structure of W-CDMA physical layer [4] that assumes QPSK modulated data streams assembled into 10 ms frames delivering data rate of 2 Mb/s in 5 MHz bandwidth. A base station continuously sends a common pilot channel spread by unique PN code known to all users so that it can be used for channel estimation and adaptive algorithms.

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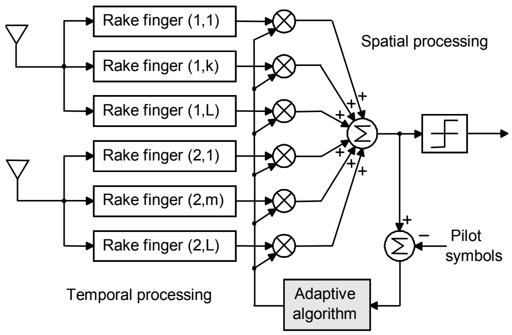

Fig. 1. MIMO W-CDMA receiver.

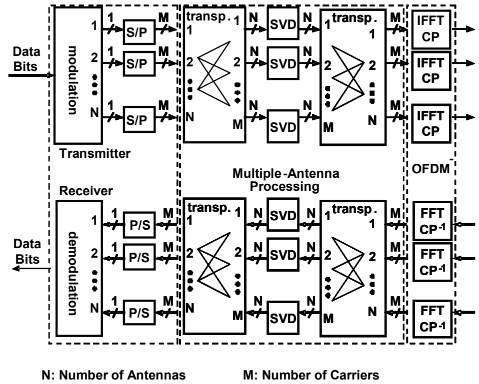

Fig. 2. MIMO OFDM transceiver.

In order to increase the capacity of the network, W-CDMA standard requires that mobile supports transmit diversity: open loop without feedback and closed loop with feedback from the receiver. In addition, mobile can be enhanced with additional receive antennas to add receive diversity gain. Due to physical and size constraints mobile receiver cannot support more than two antennas. Data streams transmitted on different antennas are spread using the same PN code. At each receiver antenna, Rake receiver is implemented by L parallel correlators locked to time offsets of the corresponding multi-paths. The outputs of the correlators produce an input to a spatial processor that optimally combines $2L$ receive paths through an adaptive algorithm, Fig. 1.

MIMO-OFDM system is designed as an extension of single-antenna OFDM system with narrowband multiple-antenna processing applied per OFDM subcarrier. We consider OFDM system with $M = 16$ sub-carriers and 2 cyclic prefix symbols to combat frequency selectivity of wireless channel. Multi-antenna processing based on singular value decomposition of a channel matrix is done before IFFT operation as illustrated in Fig. 2. The transmitter sends independent data streams across each of N transmit antennas in order to exploit multiplexing gain of MIMO channel. It also pre-filters the data to send it in the direction of eigenvectors of a channel matrix so that receiver (Rx) can exploit reduced signal space structure. Note that SVD algorithm requires that both Tx and Rx know the channel, which implies feedback.

Channel models used in the study are summarized in Table 1. Wideband MIMO channel is generated as a set of impulse responses combined with respect to Tx-Rx pairs in order to model both ISI and CCI.

3 Adaptive MIMO Algorithms for Wideband Systems

We study adaptive algorithms for MIMO systems based on Least Mean Squares (LMS) estimations [5]. In W-CDMA receiver common pilot channel is used for training, while in OFDM system we consider blind adaptation with Rx-Tx feedback [6].

W-CDMA systems exploit *multi-path diversity*. At the receiver, we allocate Rake finger for each channel multi-path. Although the system has two receive antennas, they can be treated as a single antenna with twice as many multi-paths, which could ideally result in diversity gain of 2. The LMS algorithm is used to iteratively update weight coefficients of the Rake fingers after each pilot correlation in order to exploit spreading gain, with penalty for fairly slow update. The tracking capabilities of the LMS algorithm are limited when the channel conditions change rapidly. The performance is improved by

Table 1. Multi-path channel model (parameters).

CASE I (Doppler 10 Hz)		CASE II (Doppler 10 Hz)	
Relative delay	Relative average power	Relative delay	Relative average power
0 ns	0 dB	0 ns	0 dB
976 ns	-10 dB	976 ns	0 dB
		20000 ns	0 dB

choosing optimal step size together with a leaky LMS implementation that computes weighted average rather than instantaneous estimate of the channel.

Unlike Rx, exploiting the diversity at Tx is difficult since the channel knowledge is not readily available. However, if the Tx uses space-time coding based on Alamouti scheme, then it can preserve orthogonality between signals from different antennas. We extended LMS equation for Alamouti space-time coder so that Rx performs linear processing of soft outputs from L received multi-paths. Finally, for 2x2 MIMO, combining algorithm is extended to include all received multi-paths from both antennas.

OFDM systems take advantage of *frequency diversity* of the wireless channel. Each sub-carrier of an OFDM system experiences flat-fading channel. Therefore, it is quite suitable to apply narrowband MIMO techniques on each sub-carrier. There are numerous MIMO algorithms proposed in the literature like BLAST, SVD, or QR decomposition. We consider an adaptive LMS algorithm for SVD reported in [6] that blindly tracks channel eigen-values and eigen-vectors. In this implementation, Rx computes sample autocorrelation matrix from which it estimates SVD components of the channel. Then, Rx periodically feeds optimal direction for transmission back to Tx with a rate dependent on channel Doppler.

4 Results and Discussion

We compared the performance of W-CDMA receivers with multiple Tx/Rx antennas in following {Tx, Rx} antenna combinations: {1, 1}, {1, 2}, {2, 1}, and {2, 2}. The aim is to determine what kind of channels provides maximum Tx/Rx diversity. Two distinctive channel power profiles are analyzed as described in Section 2. We compare the results with a MMSE optimal maximum ratio combining (MRC).

Figure 3 summarizes simulation results. Approximately 3-3.5 dB gain across a wide range of effective SNRs is observed in presence of two Rx antennas irrespectively of the number of Tx antennas, Fig. 3 (Case 1). In the case of a single Rx antenna, the influence of the extra Tx antenna becomes significant. A 1dB gain of transmit diversity is observed for this channel. At low SNRs there is almost no gain of adding more Tx antennas because Rx is noise-limited and cannot exploit diversity for SNR < 2dB.

In Fig. 3 (Case 2), a 3 dB gain is also observed with two Rx antennas. However, additional Tx antenna does not offer the diversity gain. This is expected result since there are two sources of diversity in the downlink: multi-path and transmit diversity. The multi-path diversity reduces the orthogonality of the downlink codes, while the transmit diversity keeps the downlink codes orthogonal in flat-fading channels. Due to equal power distribution on each multi-path, Rx does not benefit from additional Tx antennas.

SVD-based channel estimation in a 16-carrier OFDM system is simulated under average SNR = 4 dB under frequency selective fading with Doppler of 10 Hz. Due to frequency selectivity instantaneous SNRs per subcarriers are different. Figure 4 shows frequency response of a channel realization. 2x2 MIMO channel is generated using four

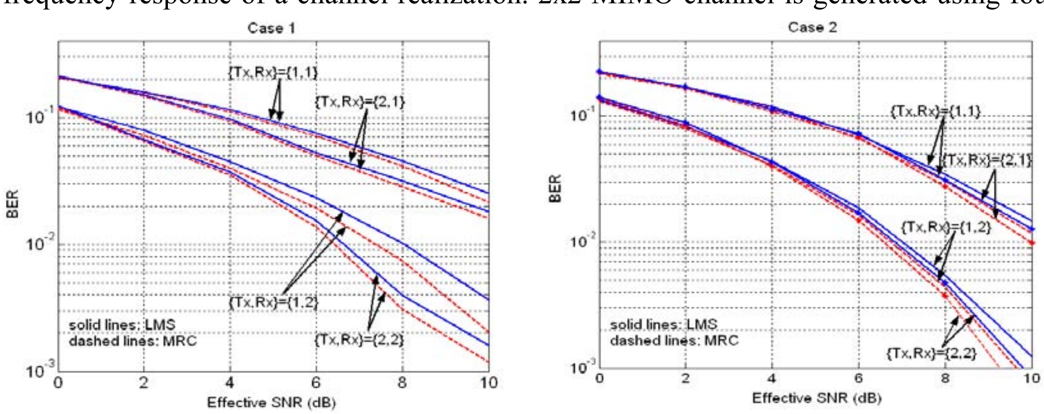

Fig. 3. BER performance of MIMO W-CDMA system.

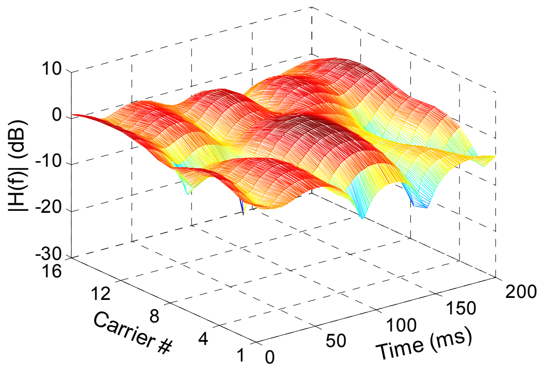

Fig. 4. Time-varying channel with 10 Hz Doppler.

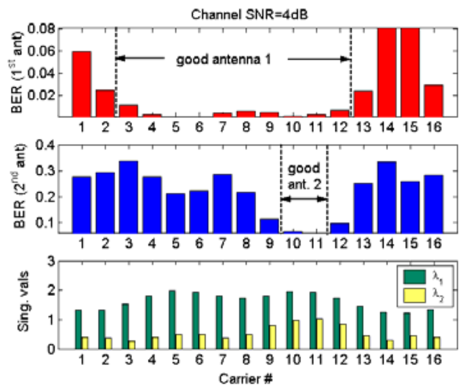

Fig. 5. BER on 16 sub-carriers.

realizations of this channel with introduced correlation between paths originating at the same Tx antenna. Figure 5 represents BER performance per sub-carrier on each Rx antenna measured over 10,000 symbols corresponding to a time interval of 10ms. During this time, the channel is approximately constant from which we observe instantaneous eigen-values shown in the plot.

Two important conclusions follow from results in Fig. 5. First, large eigen-spread does not necessarily result in good BER performance on both antennas. For example, carrier #4 has larger eigen-spread than carrier #11, but the gain of the second sub-channel is much smaller at the carrier #4 than at the carrier #11, which results in much worse BER performance and restricts this carrier to use only the dominant sub-channel. Second, there are very few carriers where both sub-channels can be used. In the case of larger number of antennas, typically the weakest sub-channel (smallest eigenvalue) is not usable. Study in [6] argued that in 4×4 case only three sub-channels are usable.

5 Conclusion

We studied MIMO algorithms for channel estimation in W-CDMA and OFDM wireless transceivers. The focus was on adaptive LMS-based algorithms. In particular, 2-D Rake receiver and space-time coder were applied to W-CDMA. Recently reported SVD-based narrow-band MIMO algorithm was applied to OFDM.

The leaky LMS approaches BER performance of ideal MMSE estimator under time-varying channel conditions. MIMO cases with up to 2 Tx/Rx antennas showed that the effective downlink SNR can be improved by about 3 dB under the Rx antenna diversity, regardless of the channel profile. The Tx diversity, however, can enhance the overall diversity gain only under certain channel profiles, with largest gains in the channels with diverse multi-path power. LMS can be used for blind tracking of SVD components of the channel matrix. The capacity gain is limited by eigen-values. BER performance is more sensitive to the value of the smallest eigen-value than to the eigen-spread. In most practical cases, thus, the sub-channels with smallest eigen-values are not usable due to poor BER.

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